Perspectives on Dark Matter

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BNL Energy Frontier
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To touch on

- Will concentrate on Direct detection and Colliders.
- How do we feel about WIMP Dark Matter in 2013?
  - MSSM
- Progress in systematizing broader parameter space
- Effective Operators and limitations

Caveats

- Axions remain a viable candidate
  - Some improvement in astrophysical bounds: Friedland, Giannotti, Wise, Phys. Rev. Lett. 110, 061101 (2013)
- Keep in mind we might be discovering only part of the Dark Matter.
- How simple is the Dark Sector? Does that dynamics change how it would be discovered?

In 2013, how do we feel about WIMPS?

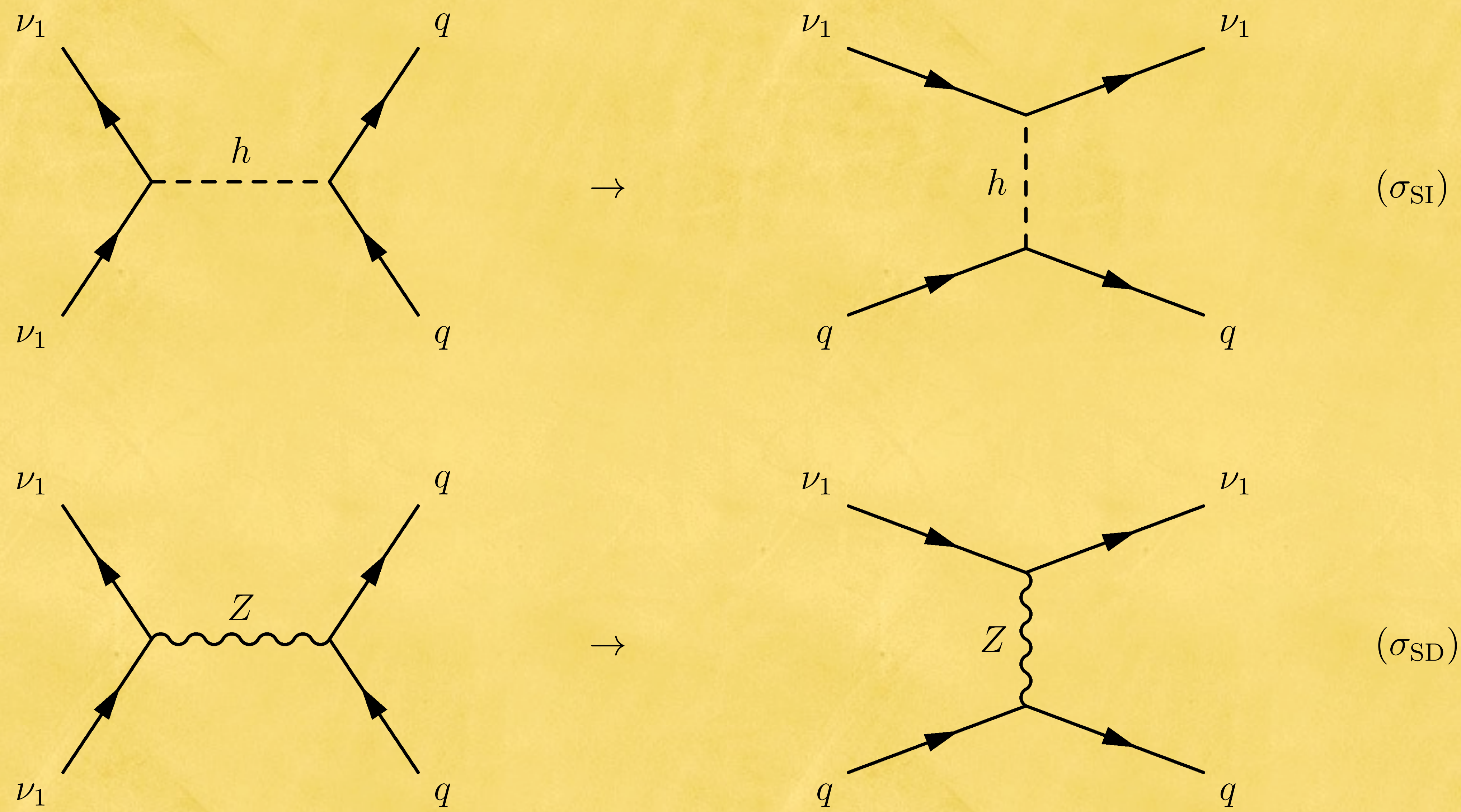
- In principle, two things could have impacted our thinking:
  - Absence of signals at direct, collider, and indirect experiments
  - Discovery of the Higgs boson

On the Higgs

- Sharpens the naturalness question: appears there is a light scalar dof responsible for EWSB (see h to ZZ, WW with about the right size)
- What is stabilizing its mass?
- What does its mass tell us?

Minimal Approach

- Not colored
- Not charged
- No new bosons?
    - Z or Higgs, Wimp with a capital W


ν_1
q
h
ν_1
q
$\rightarrow$
ν_1
ν_1
h
q
q
$(\sigma_{\rm SI})$
ν_1
q
Z
ν_1
q
$\rightarrow$
ν_1
ν_1
Z
q
q
$(\sigma_{\rm SD})$

Z boson

$$\sigma \approx \frac{G_F^2}{2\pi}\mu_{XN}^2\frac{1}{A^2}((1-4\sin^2\theta_W)Z-(A-Z))^2 Y_{ave}$$

- If chiral (heavy neutrino, e.g.) then the cross section is ``ginormous''. (~7×10^{-39} cm^2)

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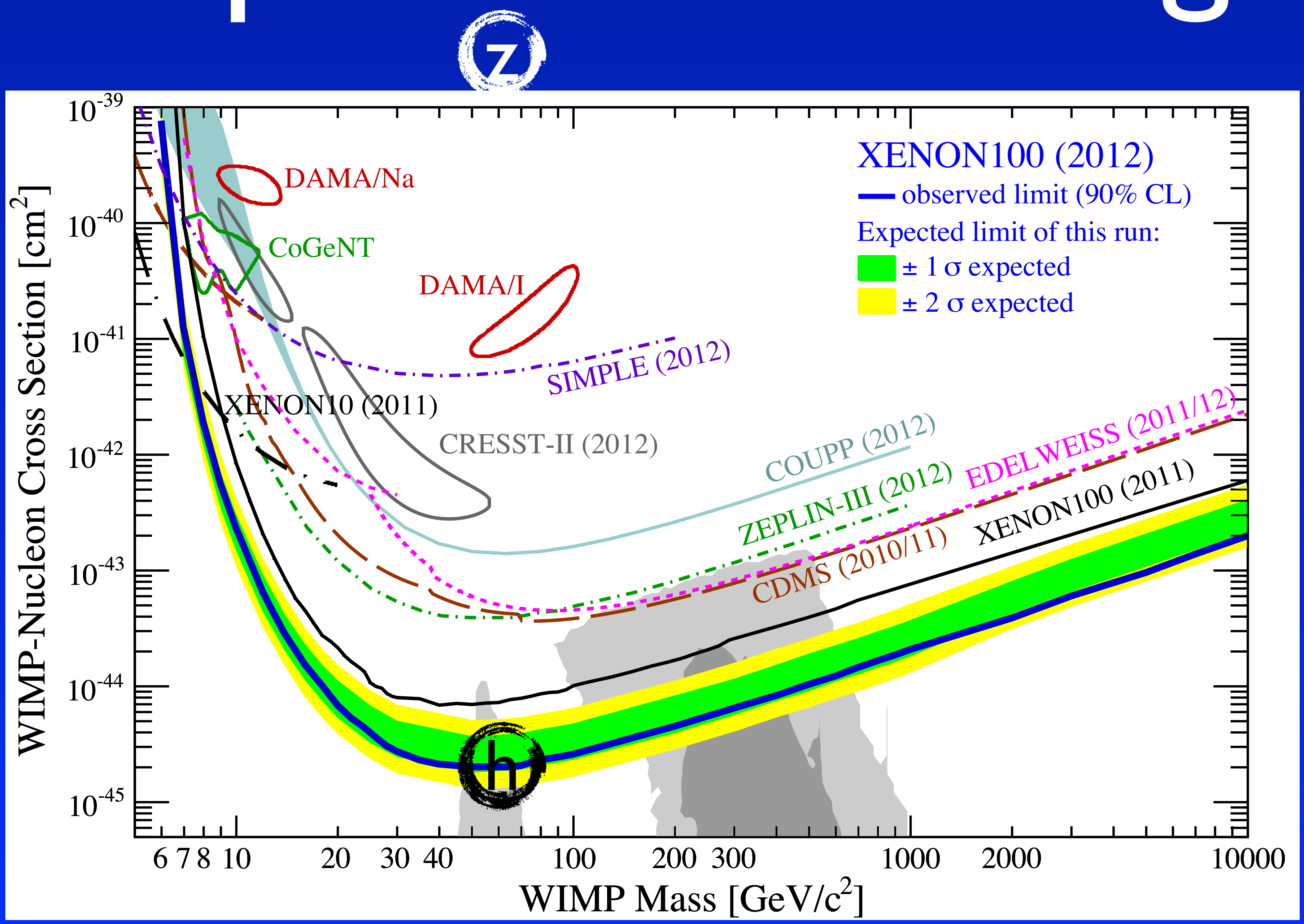
Remarkable Experimental Progress



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Z boson

$$\sigma \approx \frac{G_F^2}{2\pi}\mu_{XN}^2\frac{1}{A^2}((1-4\sin^2\theta_W)Z-(A-Z))^2 Y_{ave}$$

- If chiral (heavy neutrino, e.g.) then the cross section is ``ginormous''. (~fewx10^{-39} cm^2)
- Suppress this vectorial coupling.
- Automatic if Dark Matter is Majorana

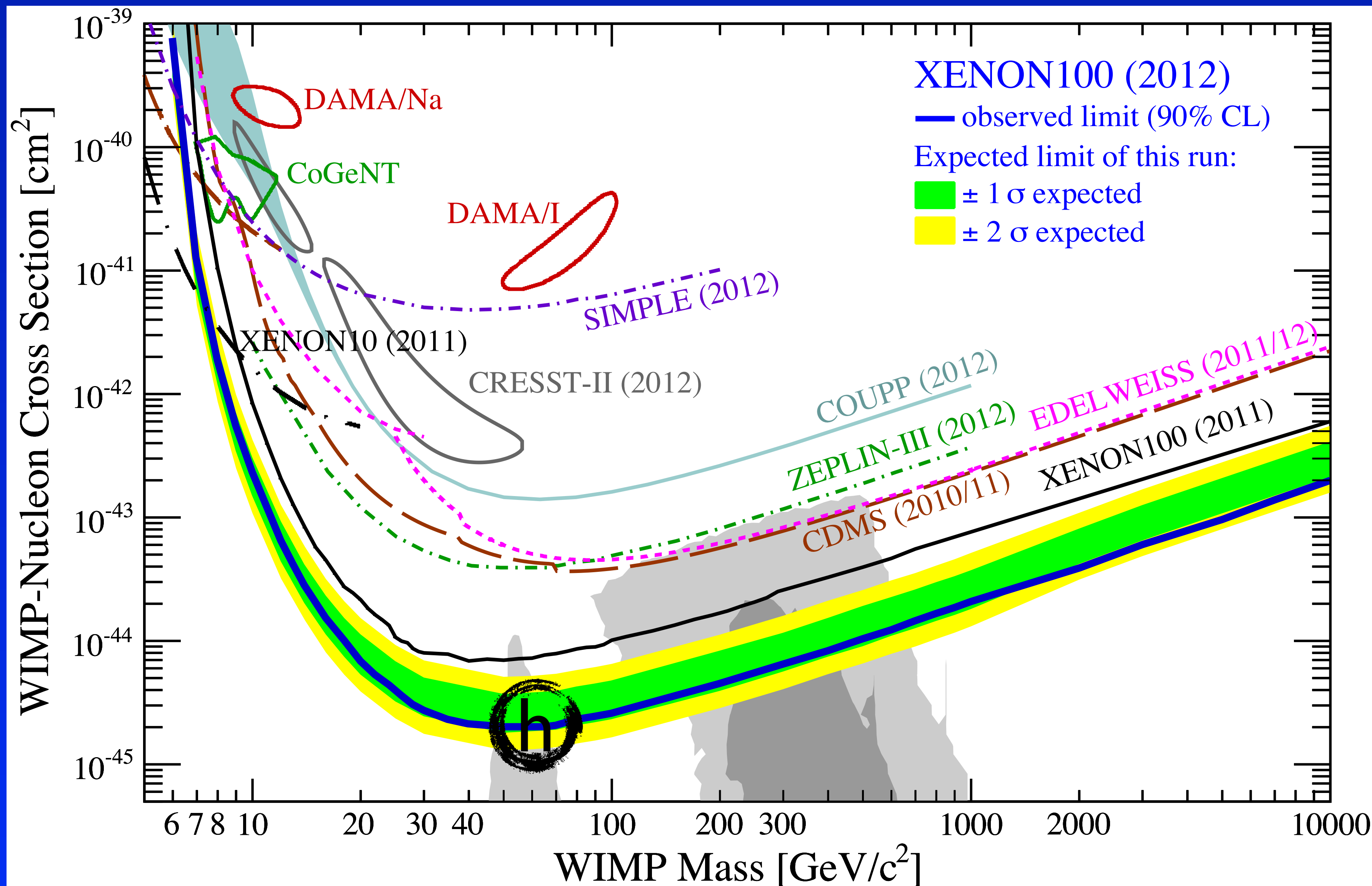
Higgs Boson Exchange

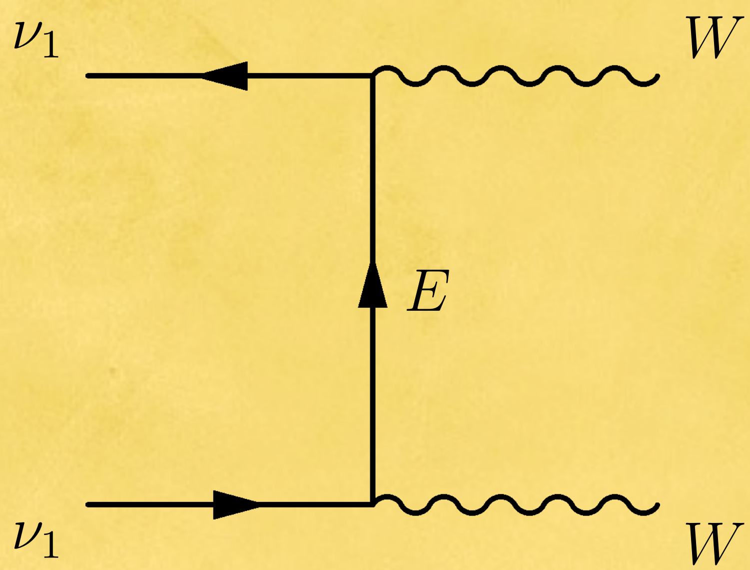
$$\sigma_{SI}(\chi N \to \chi N) \approx 8 \times 10^{-45}\mathrm{pb}\left(\frac{\mathrm{y}_\chi}{0.1}\right)^2$$

--Thermal Relics?

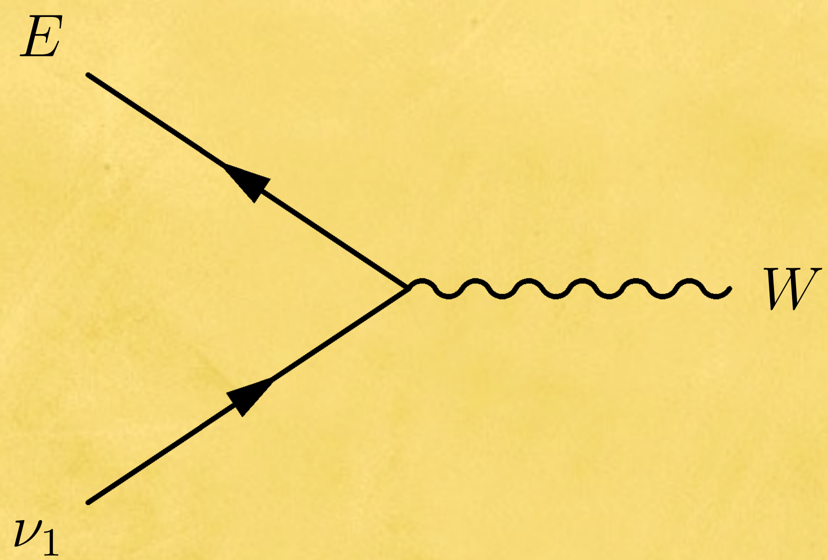
--Resonances?

--Cancellations?


XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]



$\rightarrow$ No tree-level direct detection analog



$\rightarrow$ No tree-level direct detection analog

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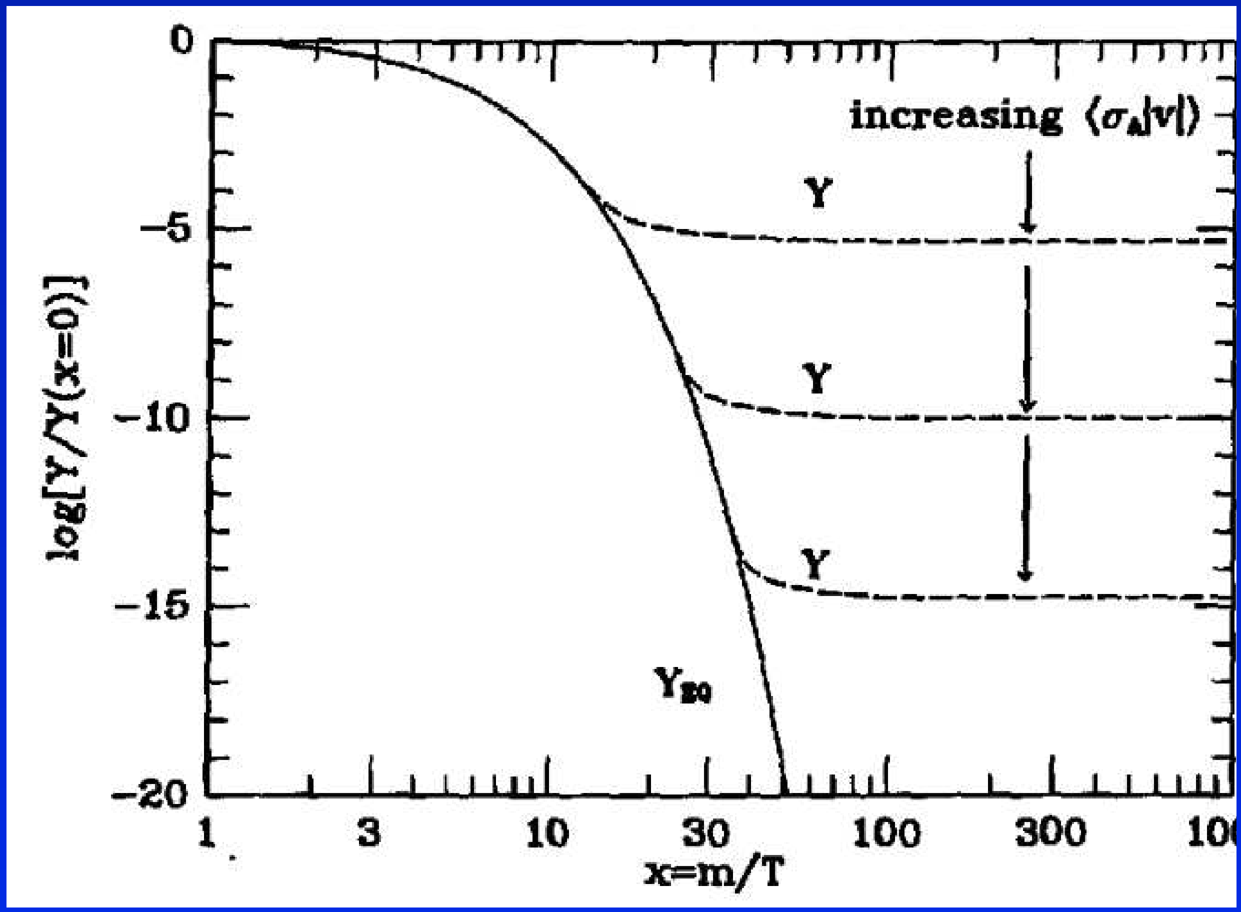
Neutralino Masses

$$M_\chi \quad = \quad \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v\cos\beta & \frac{1}{2}g'v\sin\beta \\ 0 & M_2 & \frac{1}{2}gv\cos\beta & -\frac{1}{2}gv\sin\beta \\ -\frac{1}{2}g'v\cos\beta & \frac{1}{2}gv\cos\beta & 0 & -\mu \\ \frac{1}{2}g'v\sin\beta & -\frac{1}{2}g'v\cos\beta & -\mu & 0. \end{pmatrix}.$$

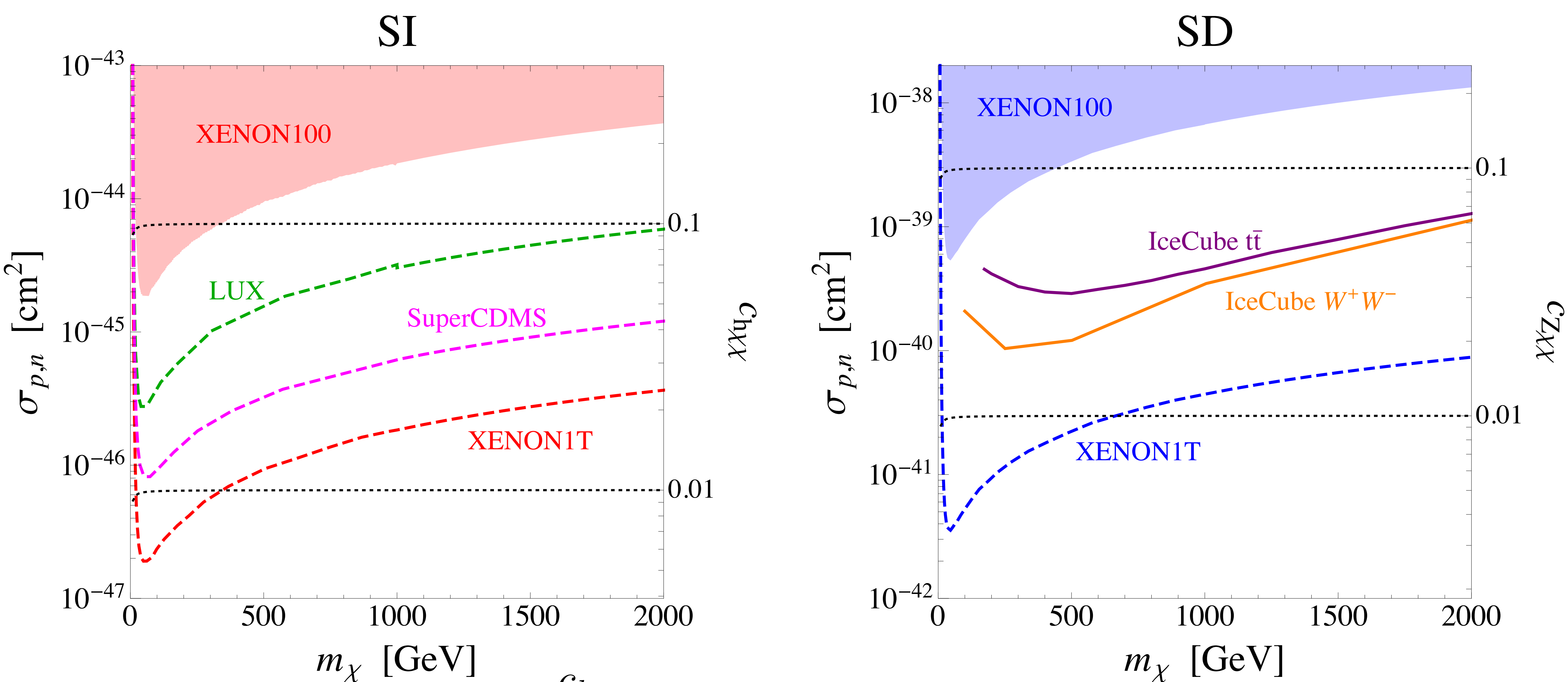
Thermal History



"Bino"

"Wino/Higgsino"

Direct Detection Status



$$\mathcal{L} \supset \frac{c_{h\chi\chi}}{2}\, h(\chi\chi + \chi^\dagger\chi^\dagger) \;+\; c_{Z\chi\chi}\,\chi^\dagger\bar{\sigma}^\mu\chi Z_\mu,$$

Cheung, Hall, Pinner, Ruderman; 1211.487

Also, Cohen, AP, Kearney, TuckerSmith

Phys.Rev. D85 (2012) 075003

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On Fine-tuning in MSSM

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

Small mu?

$$m_h \not\approx m_Z \Rightarrow$$

Need large scalar masses and/or
Large tri-linear terms

Nomura/Kitano
Baer, et al

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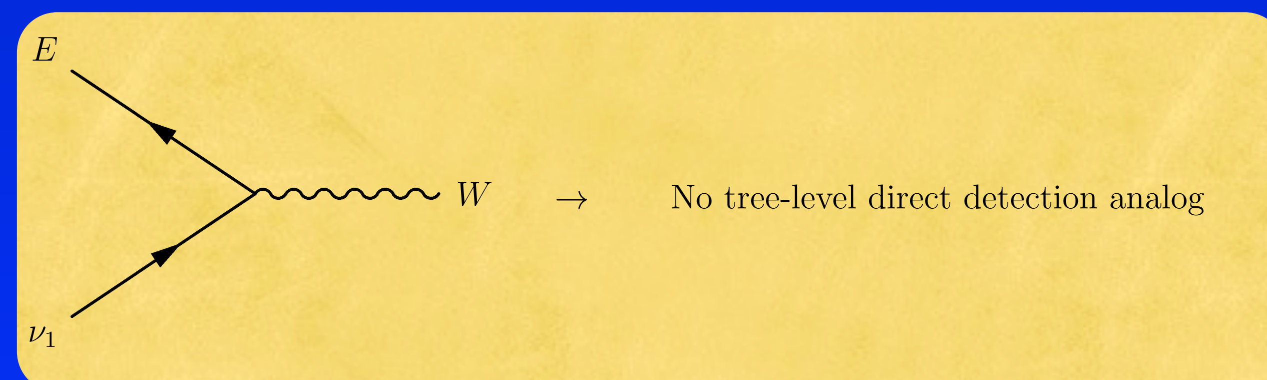
Options for correct thermal relic abundace

- Pure wino. (2.5 TeV)
- Pure higgsino. (1 TeV)
- "Well tempered" Bino/Higgsino
- Co-annhilation/Resonant annihilation
  - Find the co-conspirators!
  - Stau, stop coannihilation.
  - Hardest for Direct Detection

Junji Hisano, Koji Ishiwata, Natsumi Nagata. **Phys.Rev. D87 (2013) 035020**

see also: Hill, Solon.

Arvanitaki, et al., 1210.0555, Hall and Nomura, arXiv:1210.2395, Arkani-Hamed, et al, 1212.6971



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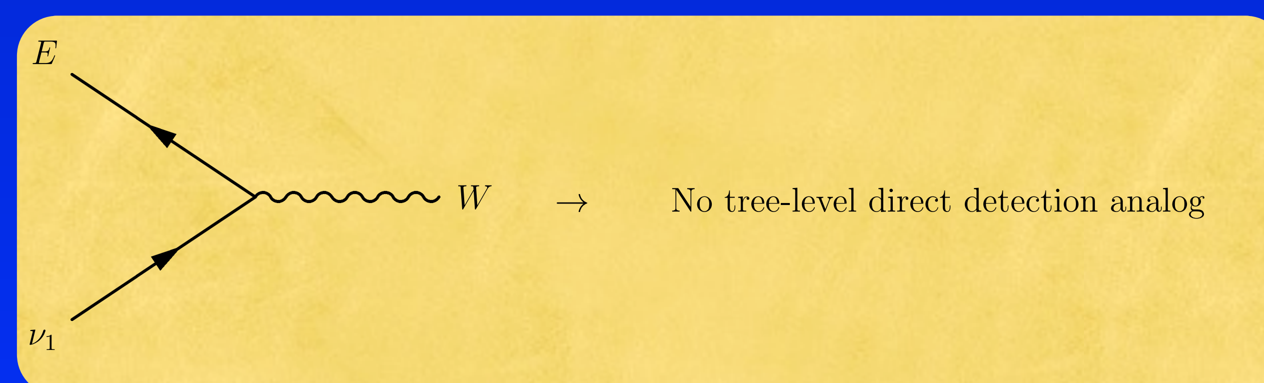

Comment on Non-Thermal histories

- Can be other sources of Dark Matter aside from thermal freeze-out
  - Moduli decay (string motivated)
  - Gravitino decay
- Often increase the relic abundance with respect to thermal, but not drastically: lighter DM.

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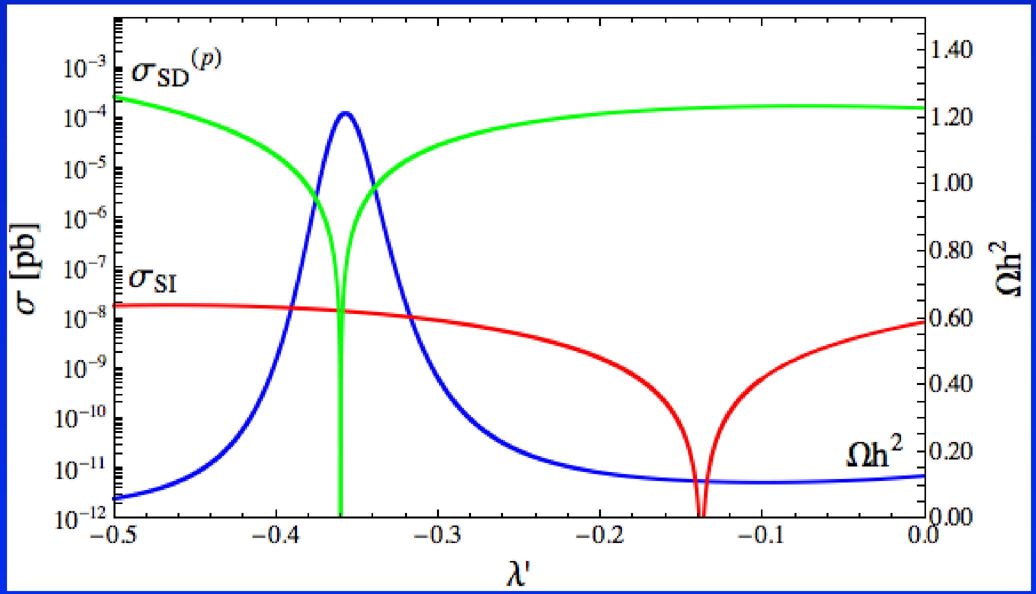
MSSM Blind Spots

m_χ	condition	signs
M_1	$M_1 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_1/\mu) = -1$
M_2	$M_2 + \mu \sin 2\beta = 0$	$\mathrm{sign}(M_2/\mu) = -1$
$-\mu$	$\tan\beta = 1$	$\mathrm{sign}(M_{1,2}/\mu) = -1^*$
M_2	$M_1 = M_2$	$\mathrm{sign}(M_{1,2}/\mu) = -1$

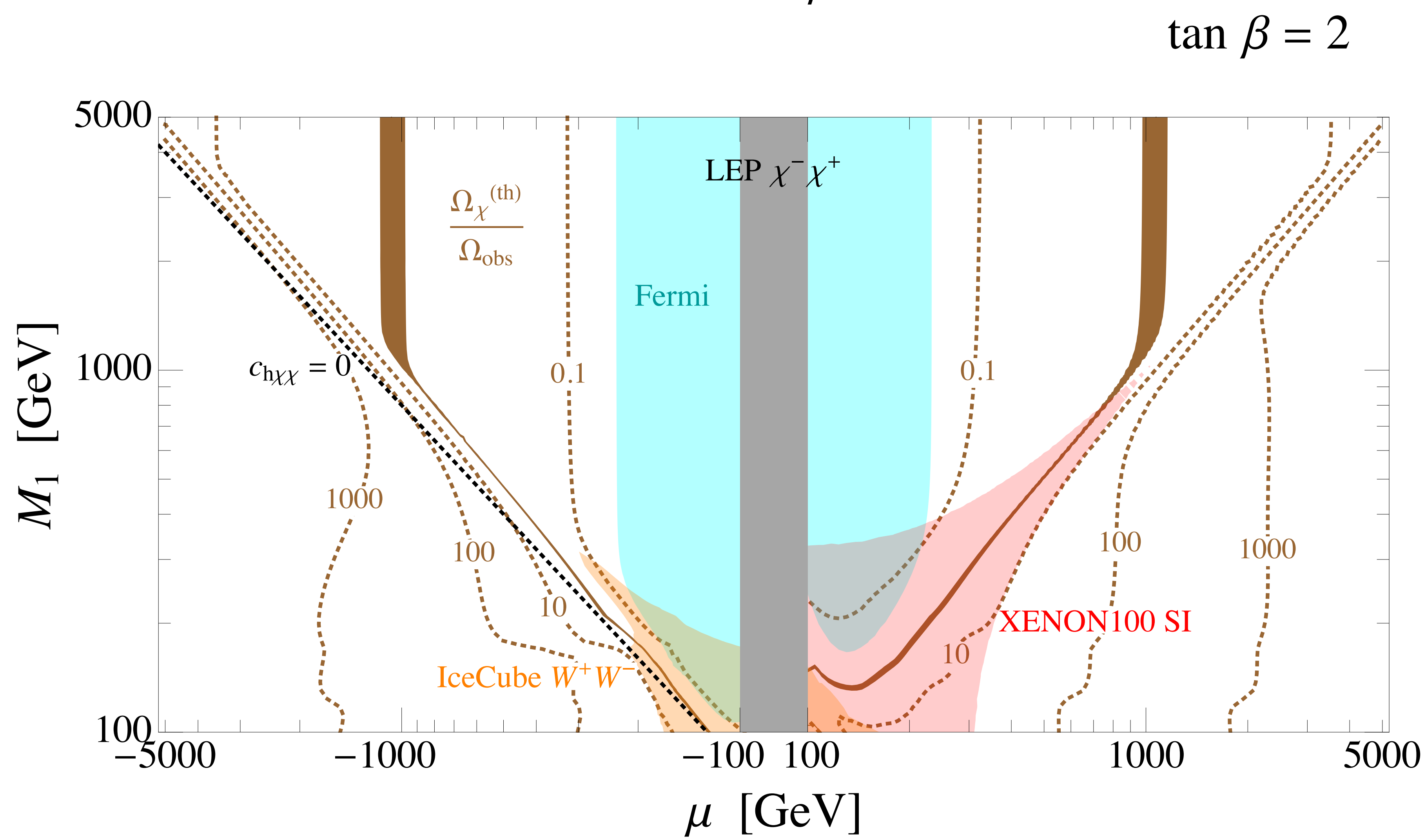
Cheung, Hall, Pinner, Ruderman



"Singlet-Doublet Model"

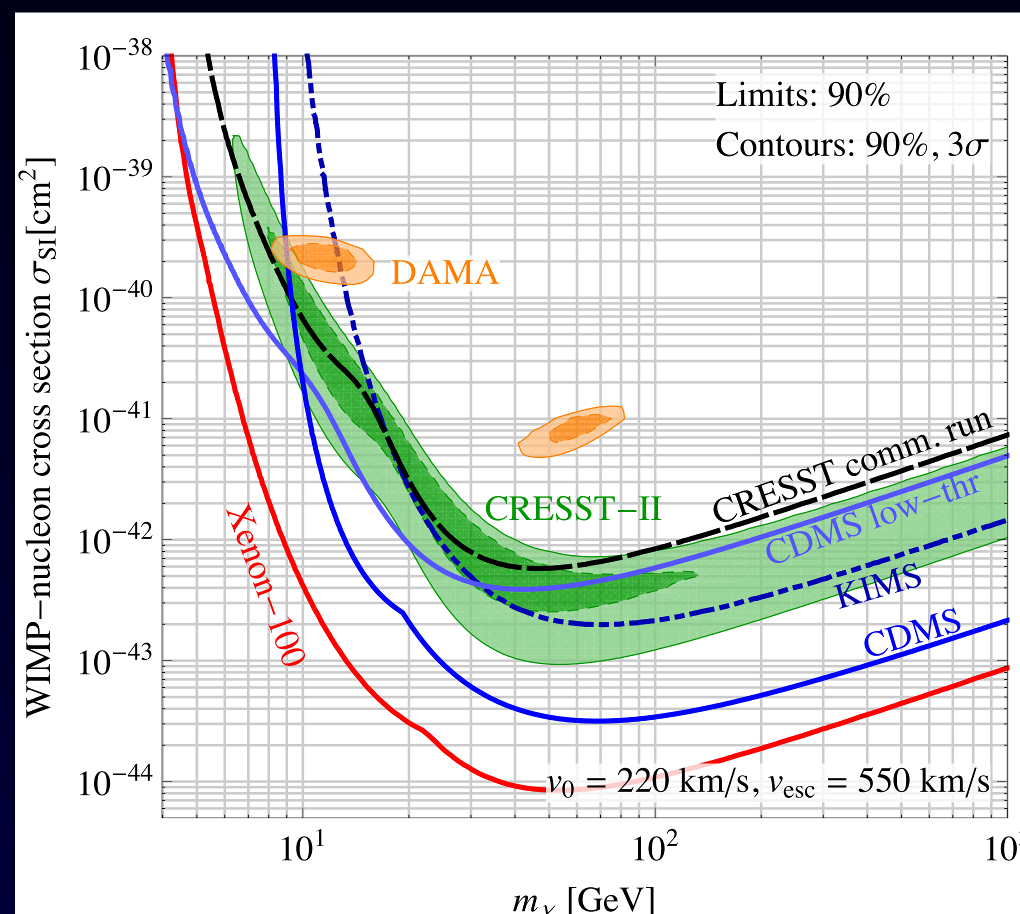
See also:Gondolo, Mandic, Murayama, AP; Cohen, Kearney, AP, Tucker-Smith 1109.2604

non−thermal $\tilde{b}/\tilde{h}$ limits



Cheung, Hall, Pinner, Ruderman

An (un)expected consequence...



Kopp, Schwetz, Zupan (2011)

Non-minimal Dark Matter Interactions

$$\begin{aligned} \mathcal{O}_{SI} &= (\bar{\chi}\chi)(\bar{q}q), \\ \mathcal{O}_{SD} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q), \end{aligned}$$

S. Chang, AP, and N. Weiner JCAP 1001 (2010) 006

Non-minimal Dark Matter Interactions

$$
\begin{aligned}
\mathcal{O}_{SI} &= (\bar{\chi}\chi)(\bar{q}q), \\
\mathcal{O}_{SD} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q),
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_1 &= (\bar{\chi}\gamma_5\chi)(\bar{q}q), \\
\mathcal{O}_2 &= (\bar{\chi}\chi)(\bar{q}\gamma_5 q), \\
\mathcal{O}_3 &= (\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q), \\
\mathcal{O}_4 &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q).
\end{aligned}
$$

S. Chang, AP, and N. Weiner JCAP 1001 (2010) 006

Non-Minimal

- Dipole Dark Matter
- Inelastic Dark Matter
- Form Factor Dark Matter
- Electronic Interactions
- Rayleigh DM
- Composite DM
- Quirky DM
- ...

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Systematizing Low-Energy Interactions

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp),$$

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}),$$

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

Fitzpatrick, et al, arXiv:1203.3542, arXiv:1211.2818;
Fan, Reece, Wang; arXiv:1008.1591

What do UV completions look like?

Colliders

- Two approaches:
  - DM is part of a rich structure
    - If part of that rich structure is colored, then produce these guys, and see the DM in cascades (gluinos and neutralinos)
    - Learn about the structure
  - DM and effective operators

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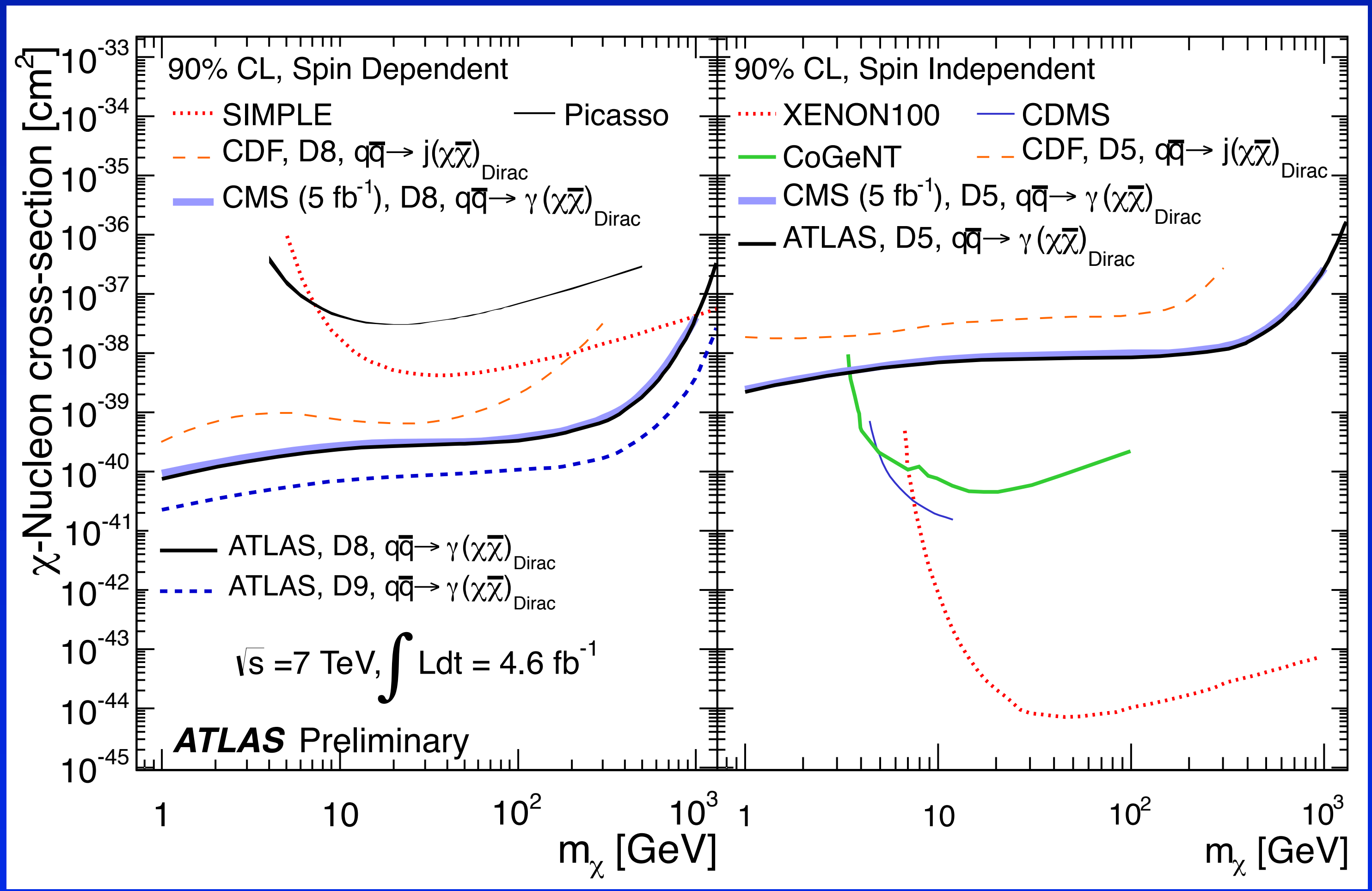
Dark Matter Operators

Look for SM SM to XX + (jet+photon)

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

- **Birkedal, Matchev, Perelstein (2004), Feng, Su, Takayama (2005), J. Goodman et al., Phys. Rev. D82, 116010 (2010), 1008.1783., Fox, Harnik, Kopp, Tsai 1103.0240; Bai, Fox, Harnik (Tevatron) JHEP 1012 (2010) 048;** Cheung, et al. 1201.3402

Colliders and DM



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-085/

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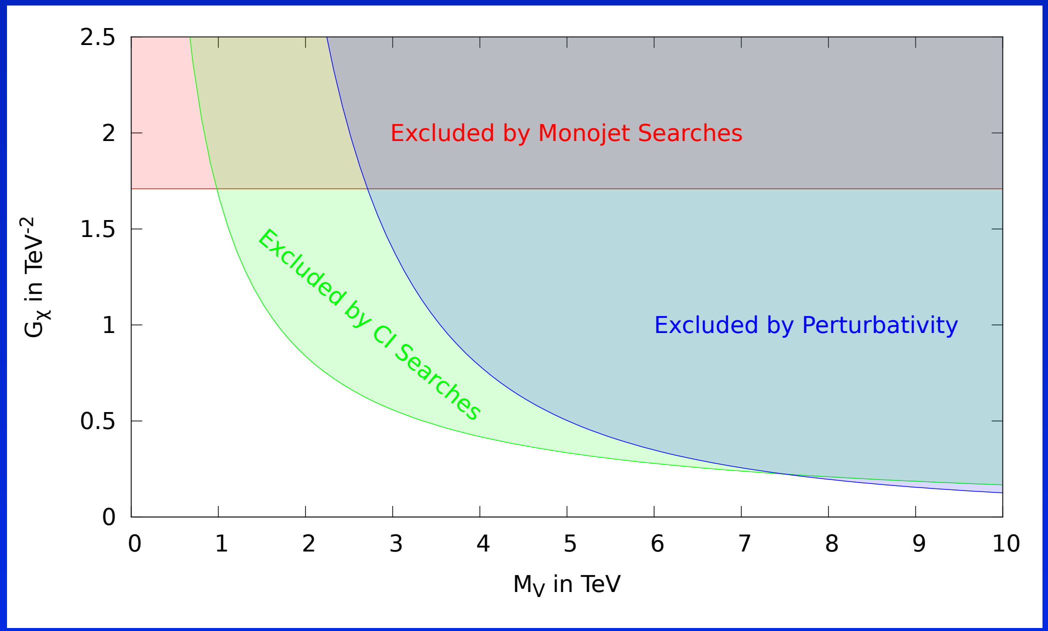
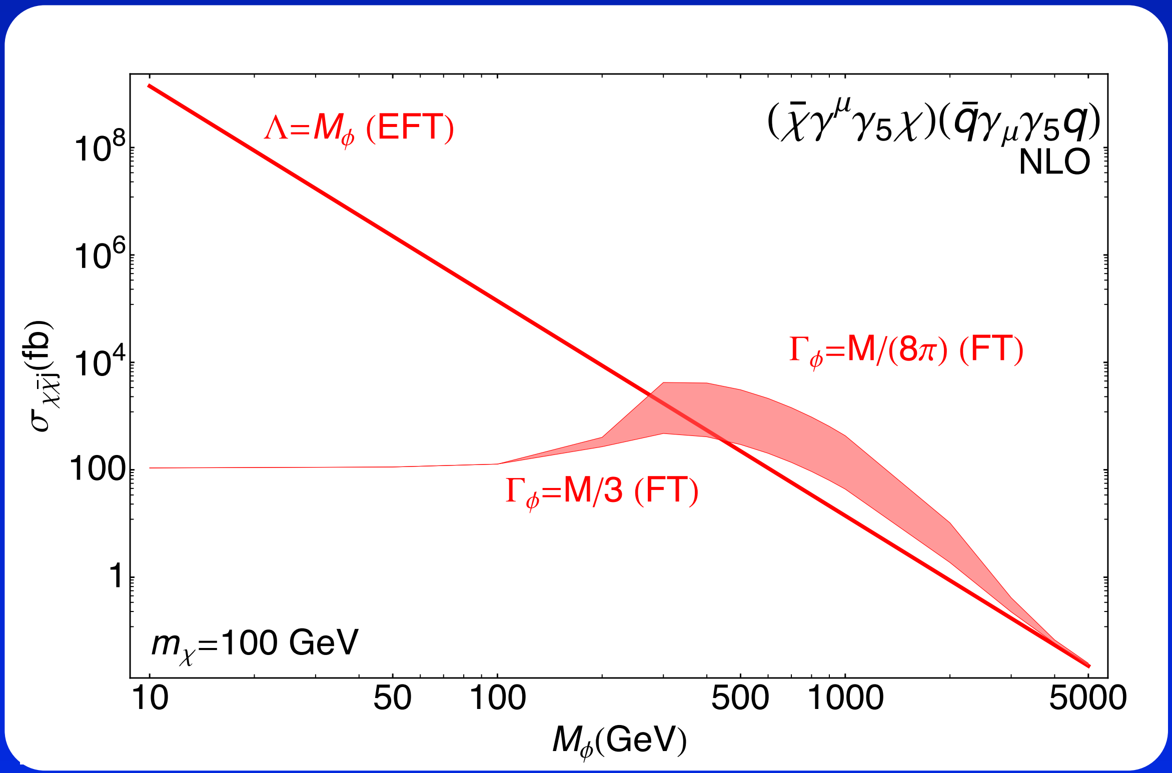
Caveats

- Apply EFT with care.
- Could get stronger bounds from other sources.
- One example: contact interactions.

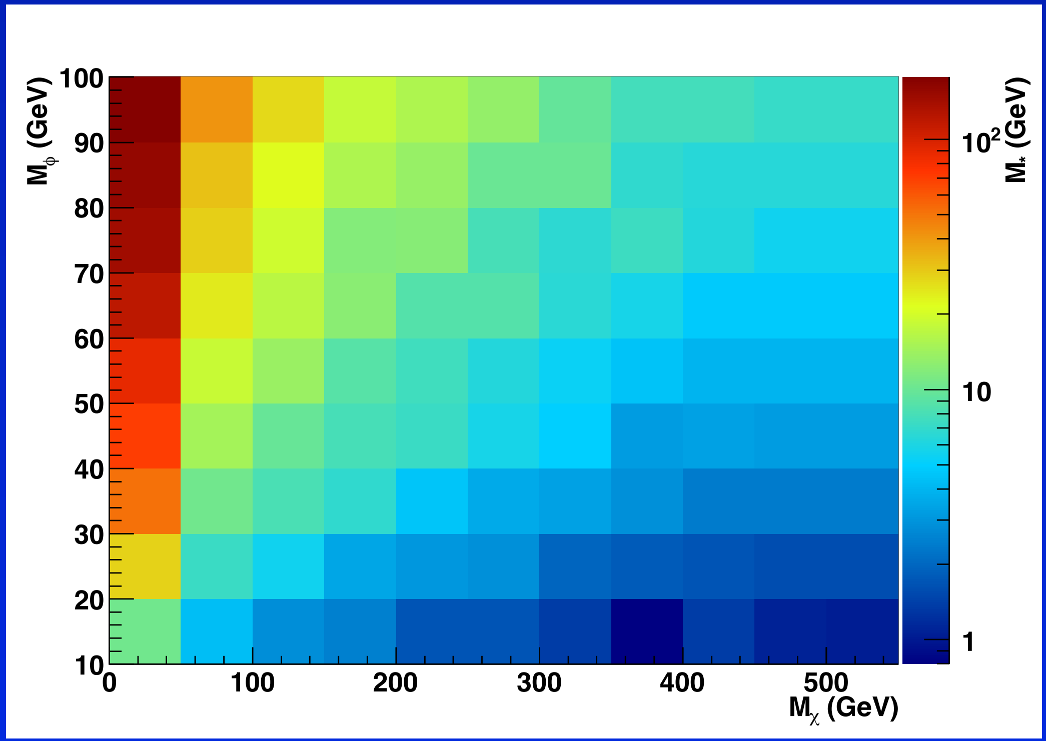


Dreiner, et al. 1303.3348

Light Mediator



Fox and Williams, 1211.6390



Goodman and Shepard, 1111.2359

Opening up the box....
H. An, Huo, and L-T. Wang, arXiv:1212.2221;
H. An, X. Ji, and L-T. Wang, arXiv:1202.2894;
Look for the associated mediator!

Effective Operators and Direct Detection

- Colliders do relatively best for light DM (small recoils make difficult for direct detection) or those operators that are velocity suppressed.
- Worth thinking more about what these UV completions look like. Also, might have light states.

  1303.6638 Lin, Kolb, L-T. Wang
- "Simplified models of DM"

  Pappucci, Vichi Zurek, in prep; Howe, this session?

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Conclusion

- WIMP dark matter alive, well, and a (the?) prime target for the next decade. Direct detection bounds are getting very interesting, but not really squeezed yet.
- Colliders do best if
  - there is a rich structure to be probed
  - effective operator would be velocity suppressed
- more effort in "Dark Matter simplified models" could be illuminating:
  - "opening the mediator box"

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